# Exploring Gluonic Matter with Electron-Ion Collisions

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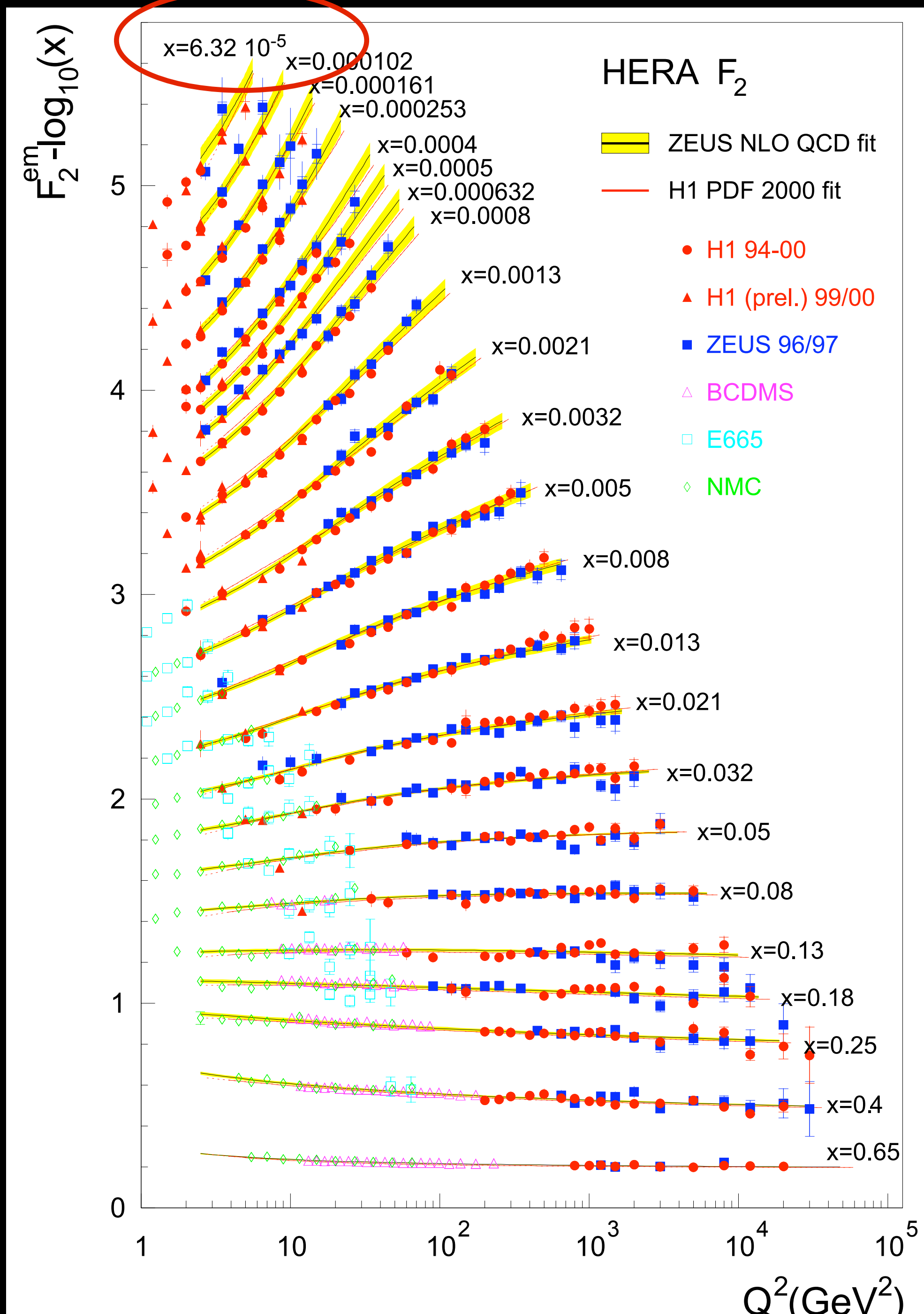
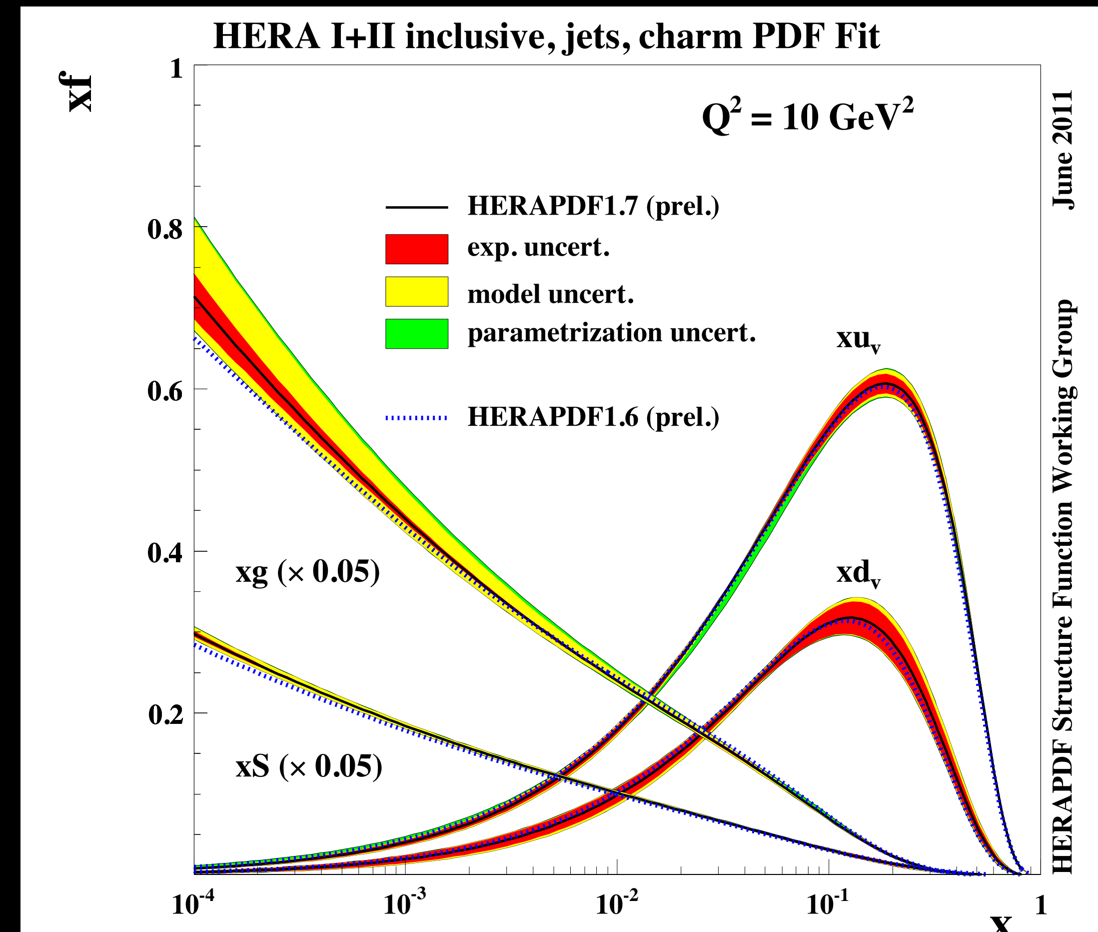
# Glue in Matter: What do we know

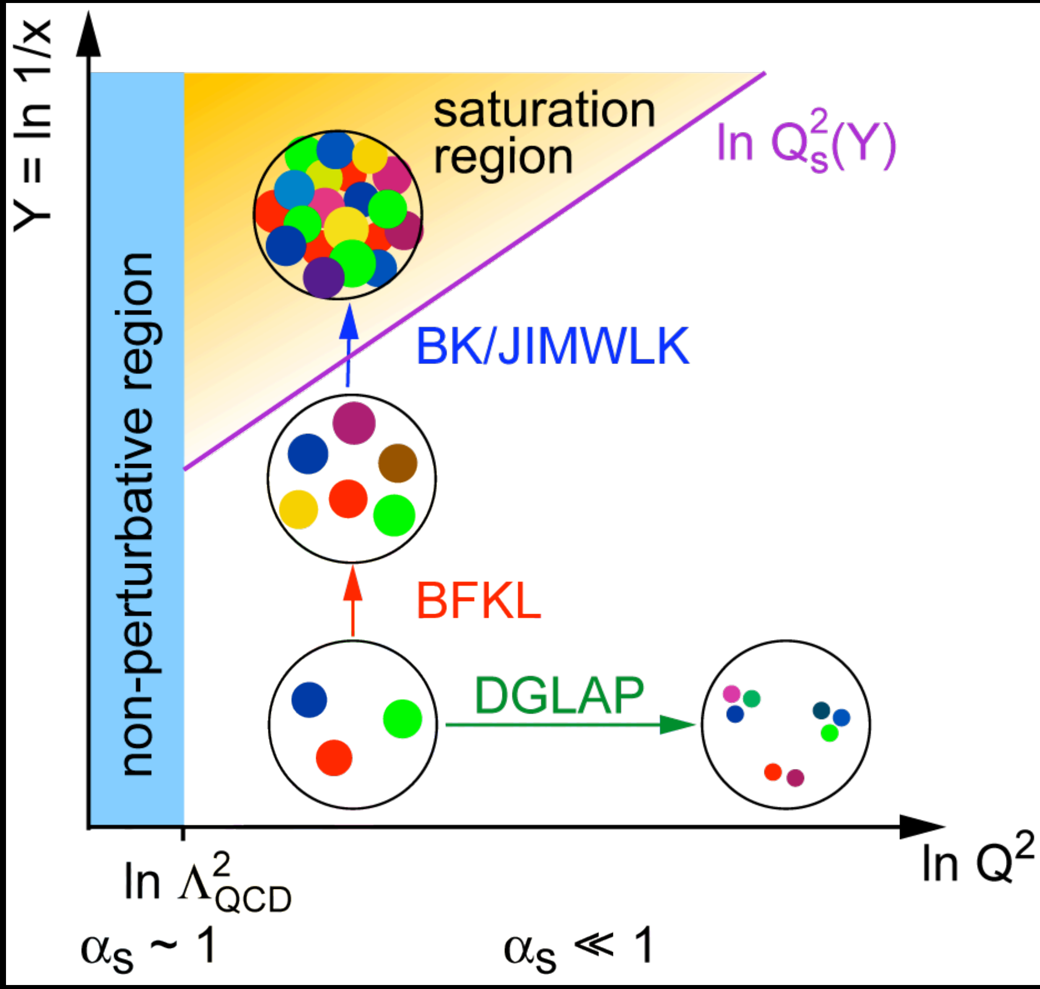


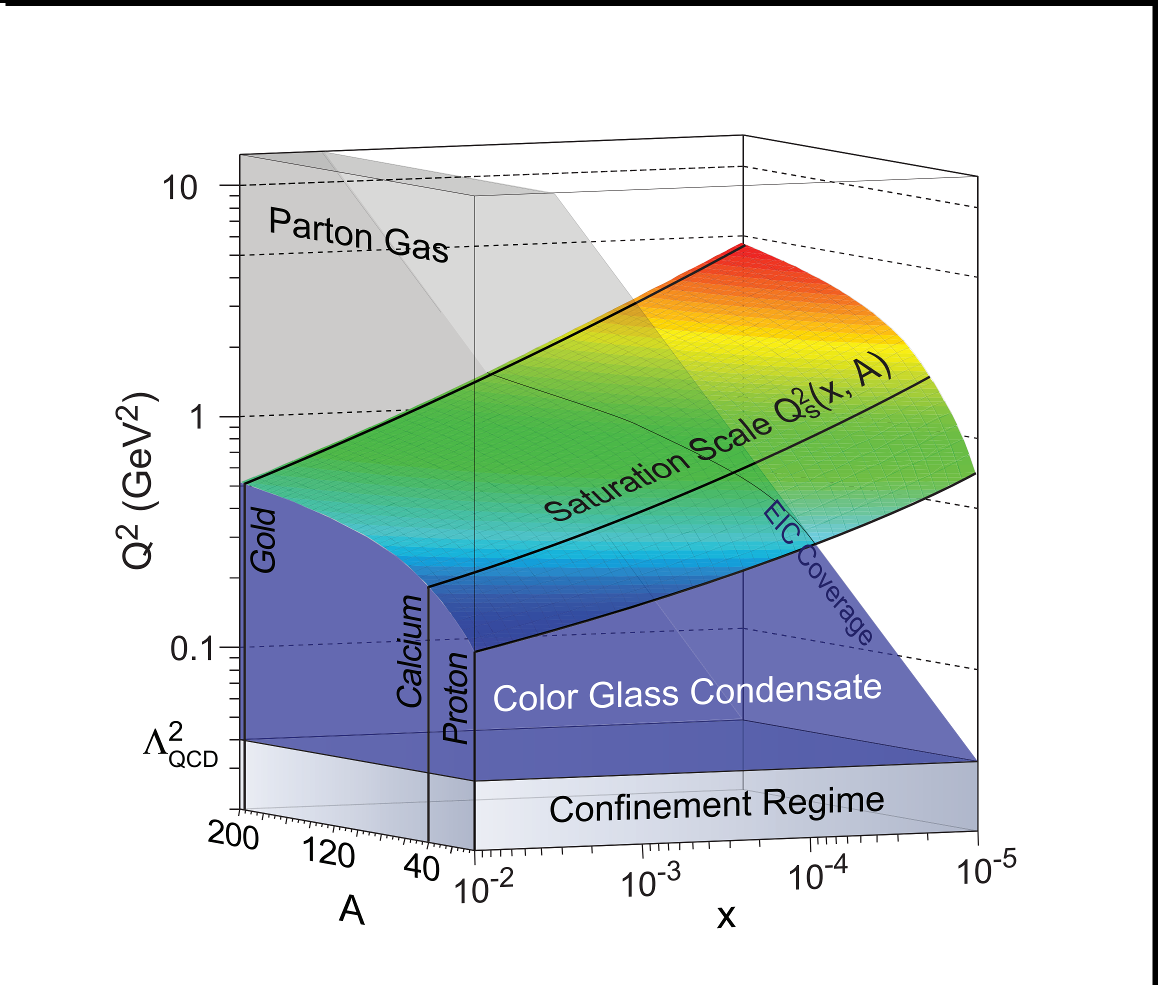




- Gluons responsible for the visible mass and drive the vacuum structure
- NLO QCD and the measurement "broadly similar": limited success
- For smaller values of x, structure function $F_2$ rises strongly with $Q^2$: Simple quark-parton model Bjorken scaling breaks
- Gluons dominate at low-x, but the underlying dynamics and the evolution is not well established

$$\frac{d^2\sigma^{ep\rightarrow eX}}{dxdQ^2} = \frac{4\pi\alpha^2_{e.m.}}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

# How gluons grow



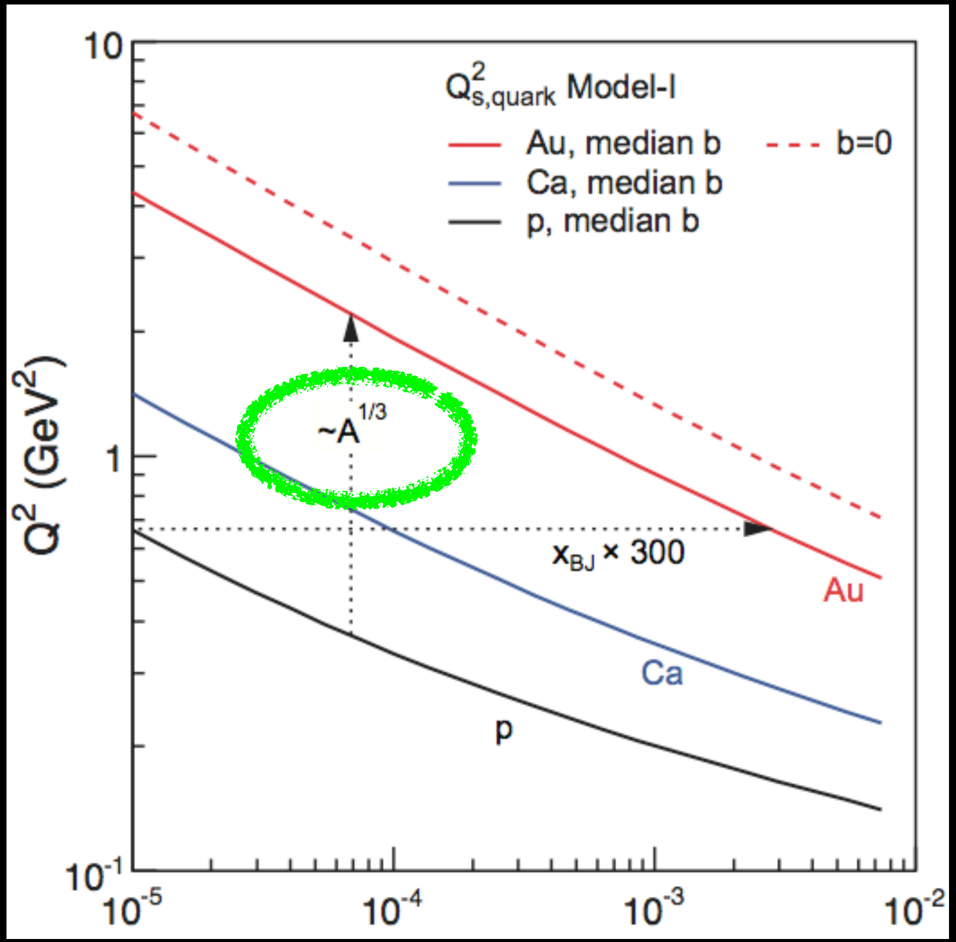




- Saturation regime arises naturally through non-linear BK/ JIMWLK evolution
  - in the Color Glass Condensate (CGC) framework
  - characterized by saturation momentum $Q_S(x,A)$
  - Experimental establishment on the "theoretical evidence" of saturation regime is fundamentally important for understanding of gluonic dynamics - strong interaction

# Estimating saturation scale

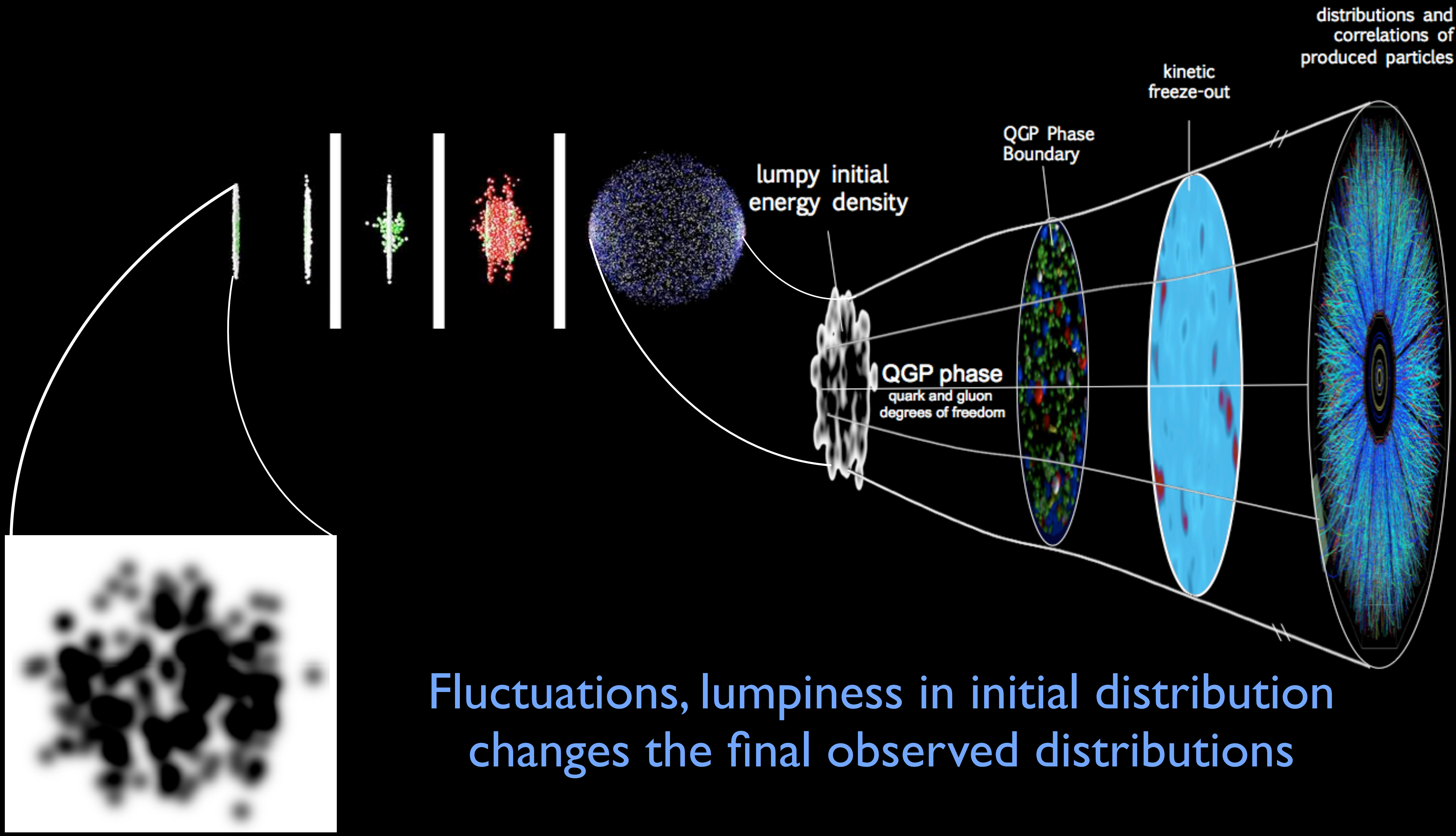
- Gluonic saturation/recombination
  - number of gluons per unit of transverse area: $\rho \sim xG(x,Q^2)/\pi R^2$
  - cross-section for gluon recombination: $\sigma \sim \alpha_s/Q^2$
  - saturation occurs when $1 < \rho\sigma \Rightarrow$

    $Q^2 < Q_s^2(x)$




- saturation Qs varies
  - Qs $\propto x^{1/3}$ (phenomenological “geometrical scaling” at HERA)
  - Qs $\propto A^{1/3}$ (Gluons act coherently)
    - **Nuclear enhanced** saturation scale
    - To access saturation: increase energy (~1/x) or **increase $Q_s$ ($\sim A^{1/3}$)**
      - HERA (ep) energy range higher $G(x,Q^2)$ very limited reach of the saturation regime: Need $\sqrt{s}$=1-2 TeV in ep

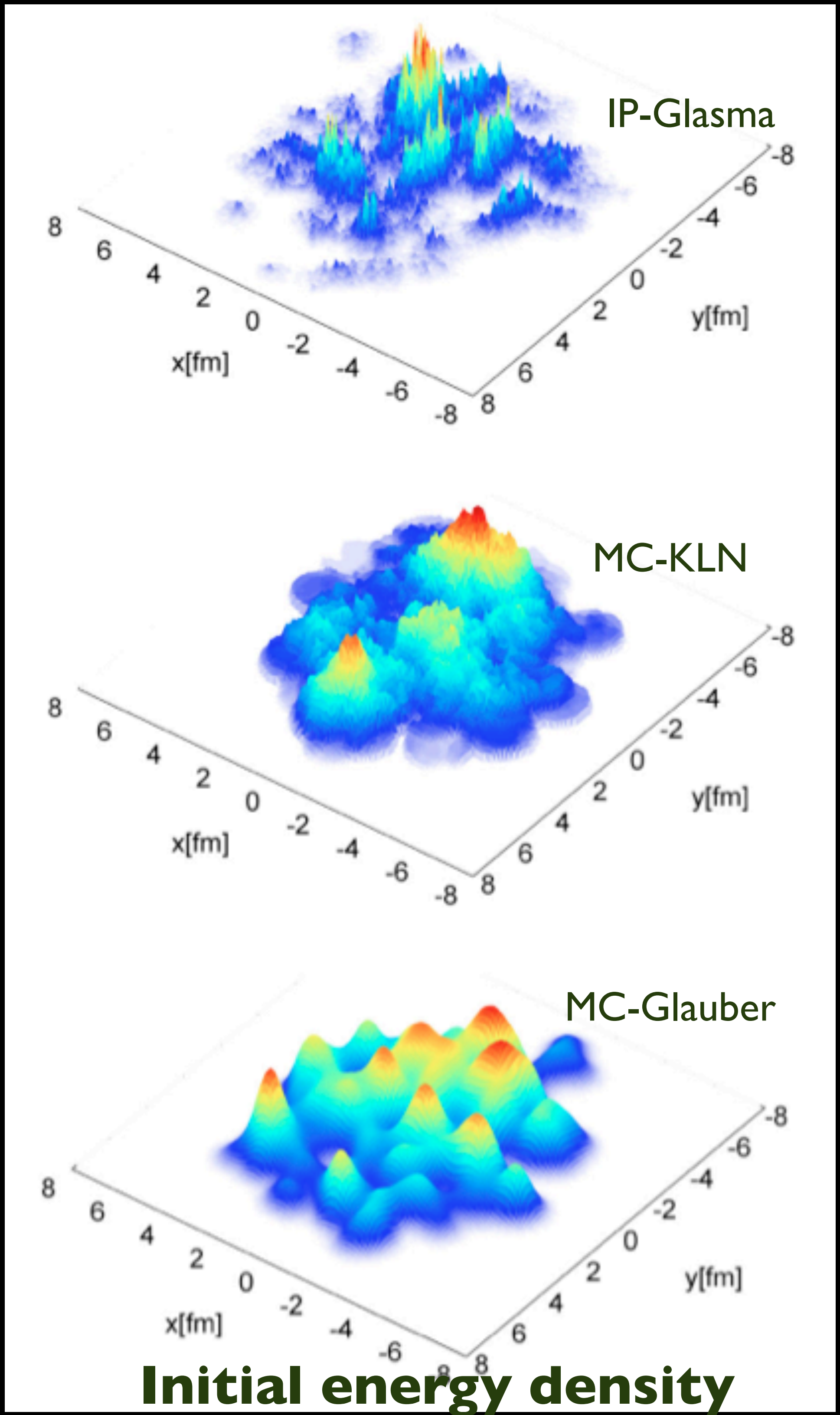
# Initial gluon distribution matters in RHI collisions



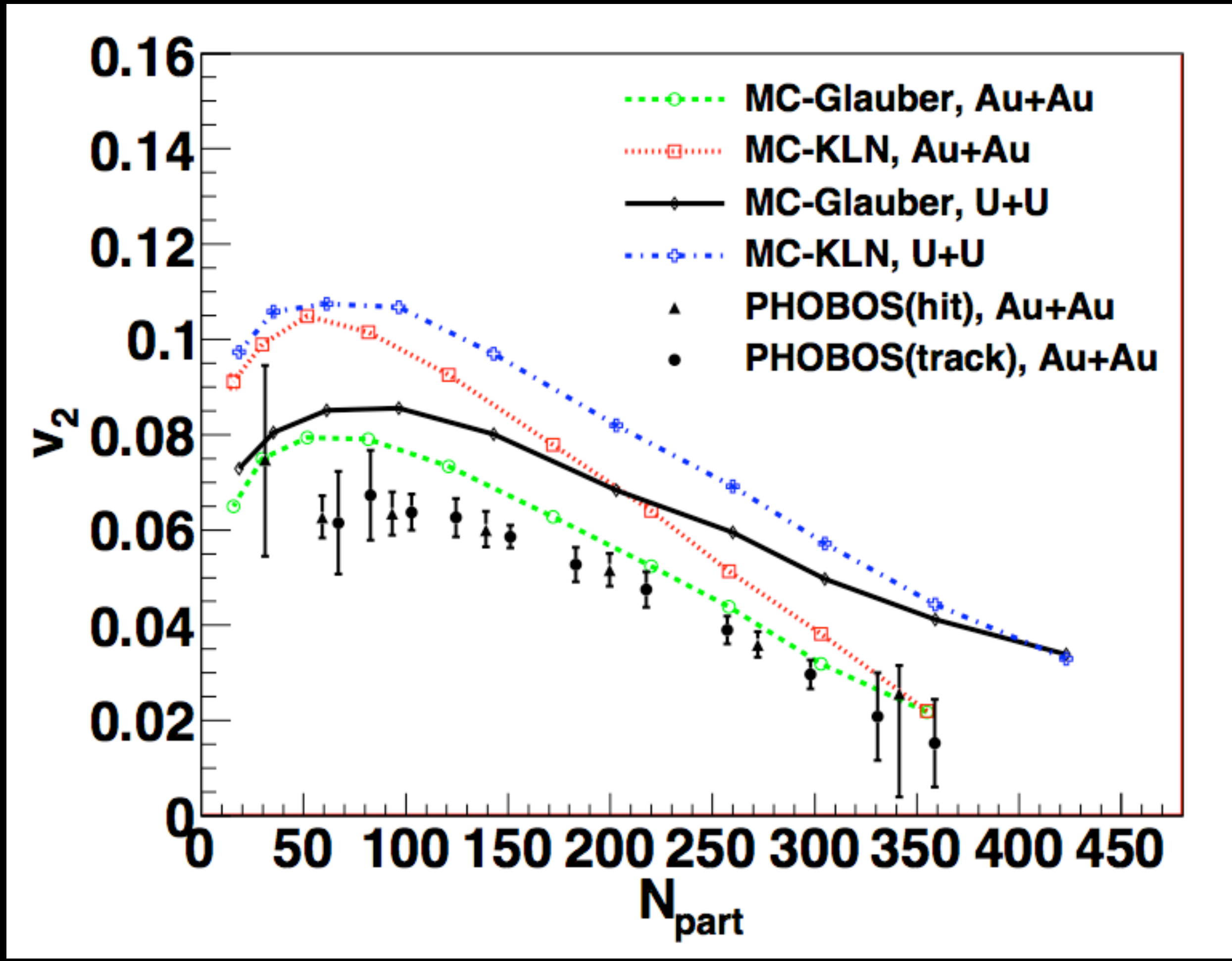

Fluctuations, lumpiness in initial distribution changes the final observed distributions

Kowalski, Lappi, Venugopalan PRL 100 (2008)

# Understanding initial gluon dynamics



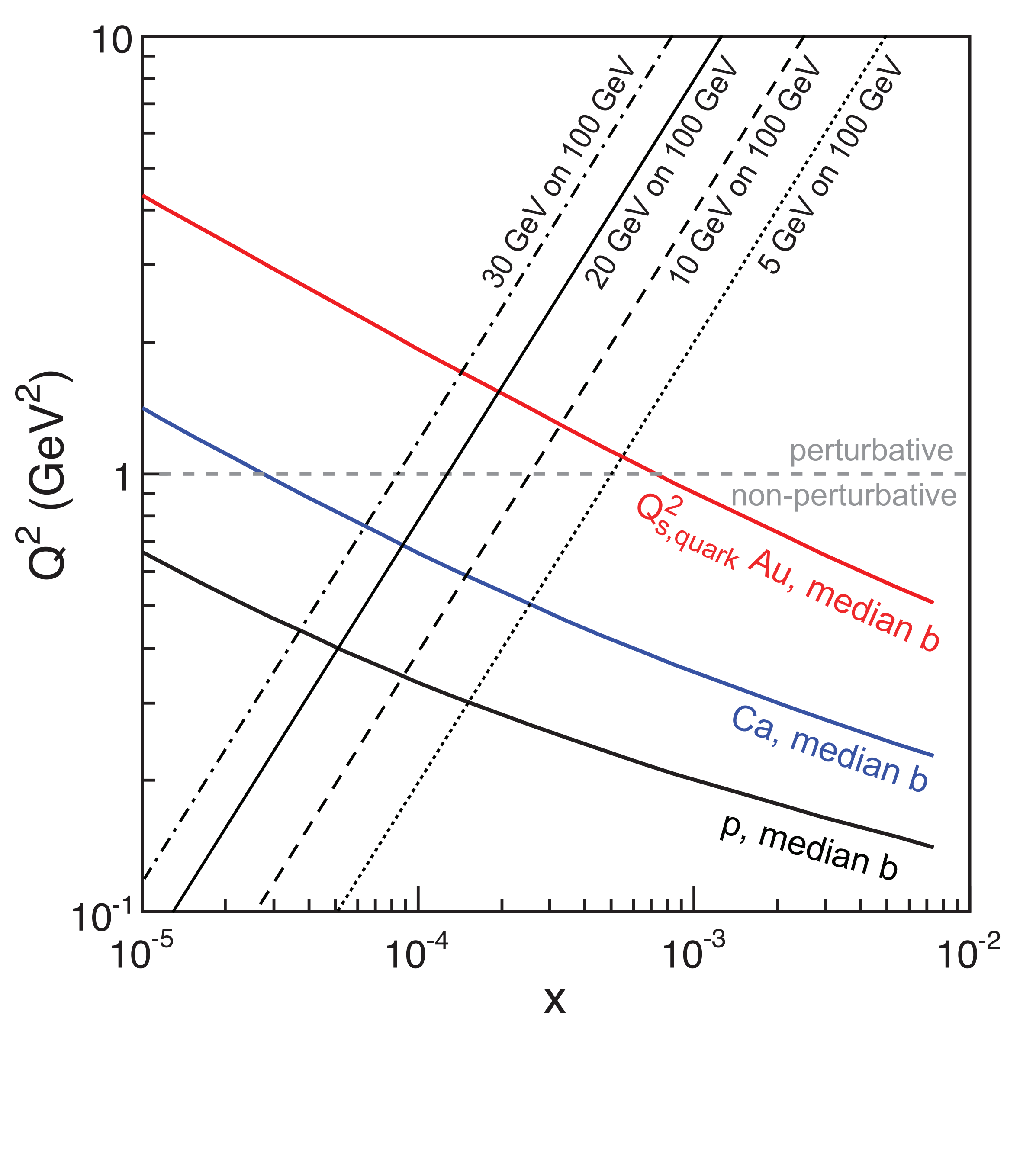

PRL 108 (2002) Schenke, Tribedy, Venugopalan




Hirano et al. arXiv:1204.5814 (2002)

Understanding initial dynamics is important for the quantitative interpretation of the medium created in relativistic heavy ion collisions.

# Electron-Ion Collider (EIC)
## exploring gluons (and sea quarks) - beyond HERA




- e + Ion : nuclear enhanced (~x300) effective small-x reach - deeply into saturation regime
- wide energy range: kinematic coverage with great leverage for measuring gluon distribution $F_L$ ($\sqrt{s_A}$=~10-100 GeV)
- high luminosity (~x500 of HERA) : rare and precision probe for gluonic properties: heavy flavor, exclusive measurements, ...
- polarized e and p: gluonic contribution to spin degree of freedom of nucleon

# Characterizing glue in matter with EIC

- Precisely mapping momentum and space-time distribution of gluons in nuclei in wide kinematic range including saturation regime through:
  - Inclusive measurements of structure functions ($F_2$, $F_L$, $F_2^D$, $F_L^D$): $eA \to eX$, $eA \to eX$+gap
  - Semi-inclusive measurements of final state distributions: $eA \to eA\{\pi, K, \Phi, D, J/\Psi ...\}X$
  - Exclusive final states: $eA \to eA\{\rho, \Phi, J/\Psi, \gamma\}$
- Multiple controls: x, $Q^2$, t, $M_X^2$ for light and heavy nuclei

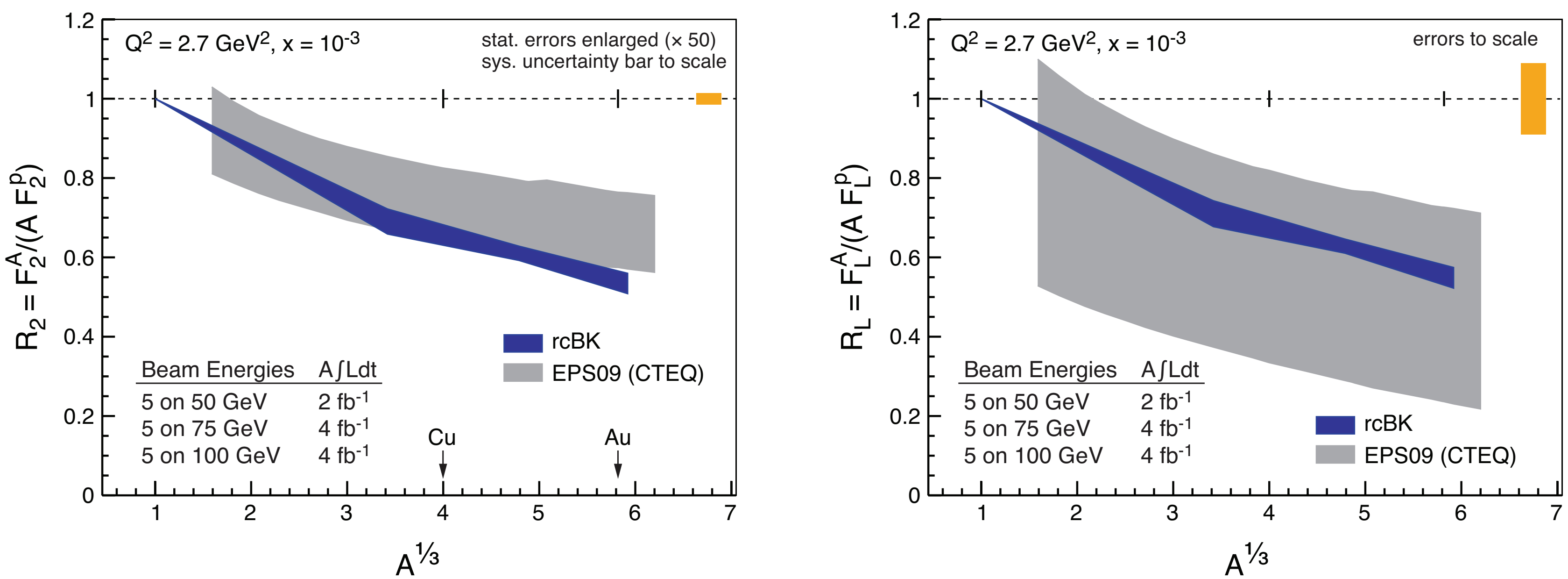
# e+A physics science matrix: Key measurements

| Deliverables | Observables | What we learn | Phase-I | Phase-II |
|---|---|---|---|---|
| integrated gluon distributions | $F_{2,L}$ | nuclear wave function; saturation, $Q_s$ | gluons at $10^{-3} < x < 1$ | saturation regime |
| $k_T$ dependent gluons; gluon correlations | di-hadron correlations | non-linear QCD evolution / universality | onset of saturation | measure $Q_s$ |
| transport coefficients in cold matter | large-x SIDIS; jets | parton energy loss, shower evolution; energy loss mechanisms | light flavors and charm; jets | rare probes and bottom; large-x gluons |
| b dependence of gluon distribution and correlations | Diffractive VM production and DVCS, coherent and incoherent parts | Interplay between small-x evolution and confinement | Moderate x with light and heavy nuclei | Extend to low-x range (saturation region) |

# Key Measurements:
# Integrated gluon distribution: $F_2$ and $F_L$

$$\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y+} F_L^A(x,Q^2)$$

$Q^2$=sxy

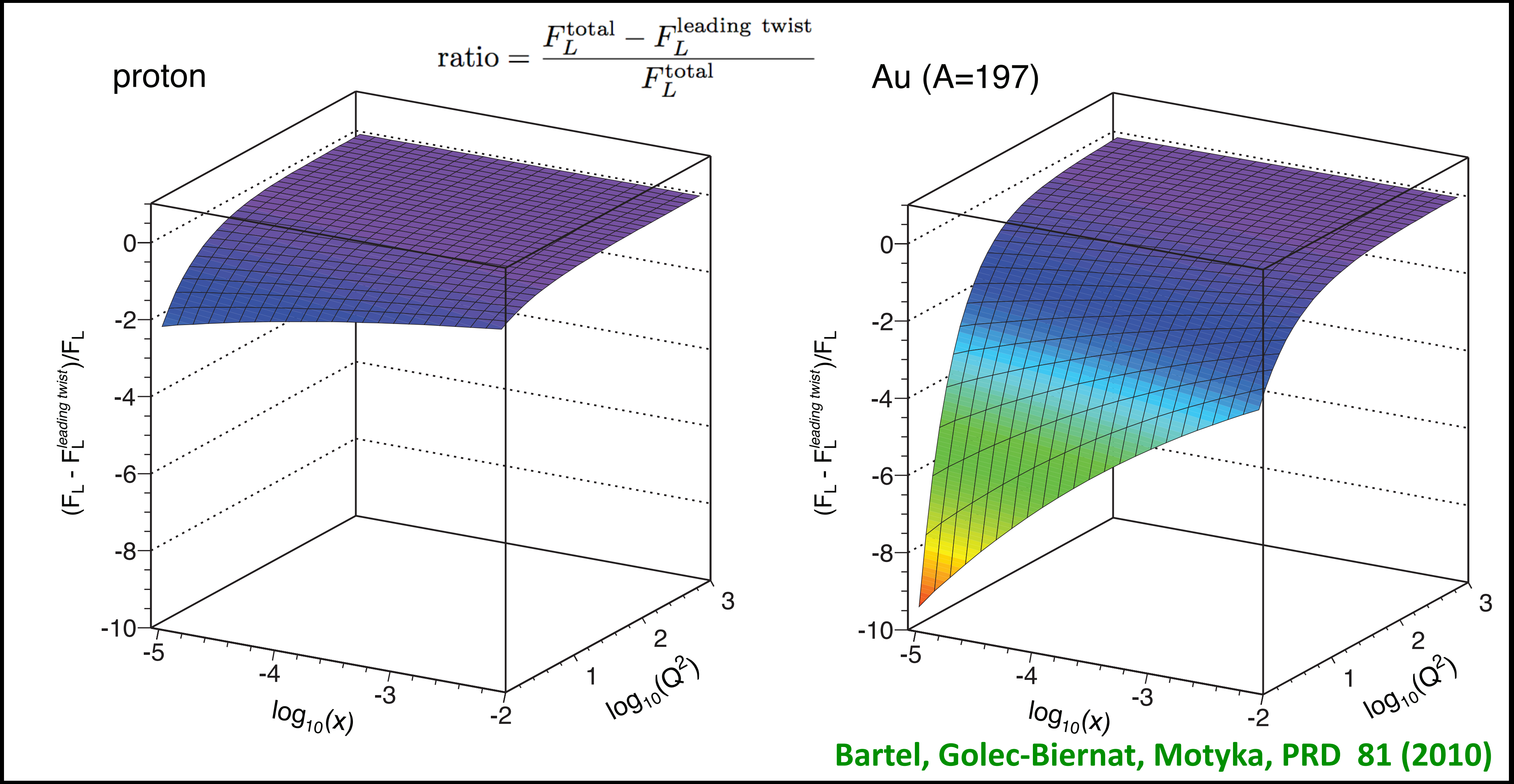



- $F_{2,L}$ extracted from pseudo-data generated at 3 EIC energies (2-4 fb$^{-1}$: 4 weeks/each)
  - 5+50 GeV
  - 5+75 GeV
  - 5+100 GeV
- Data, with errors, added to theoretical expectations from EPS09 PDF and rcBK
  - at $Q^2$ = 2.7 GeV$^2$
  - $x=10^{-3}$

# Non-linear QCD in $F_L$

$$F_L^A(x,Q^2) \propto x\,G_A(x,Q^2)$$

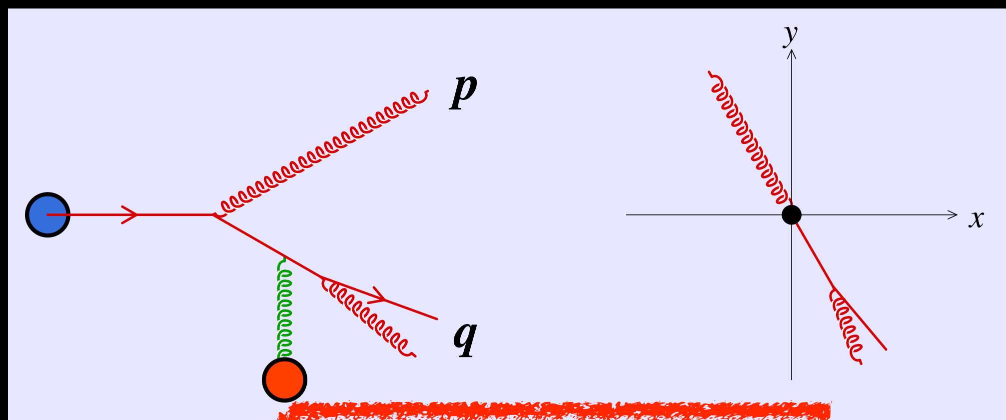
$F_L{}^A$ is sensitive to higher twist (non-linear) effects

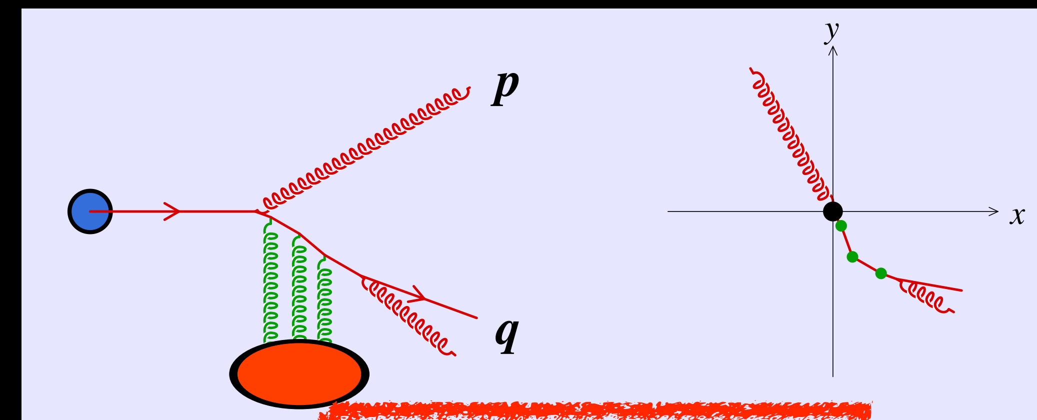


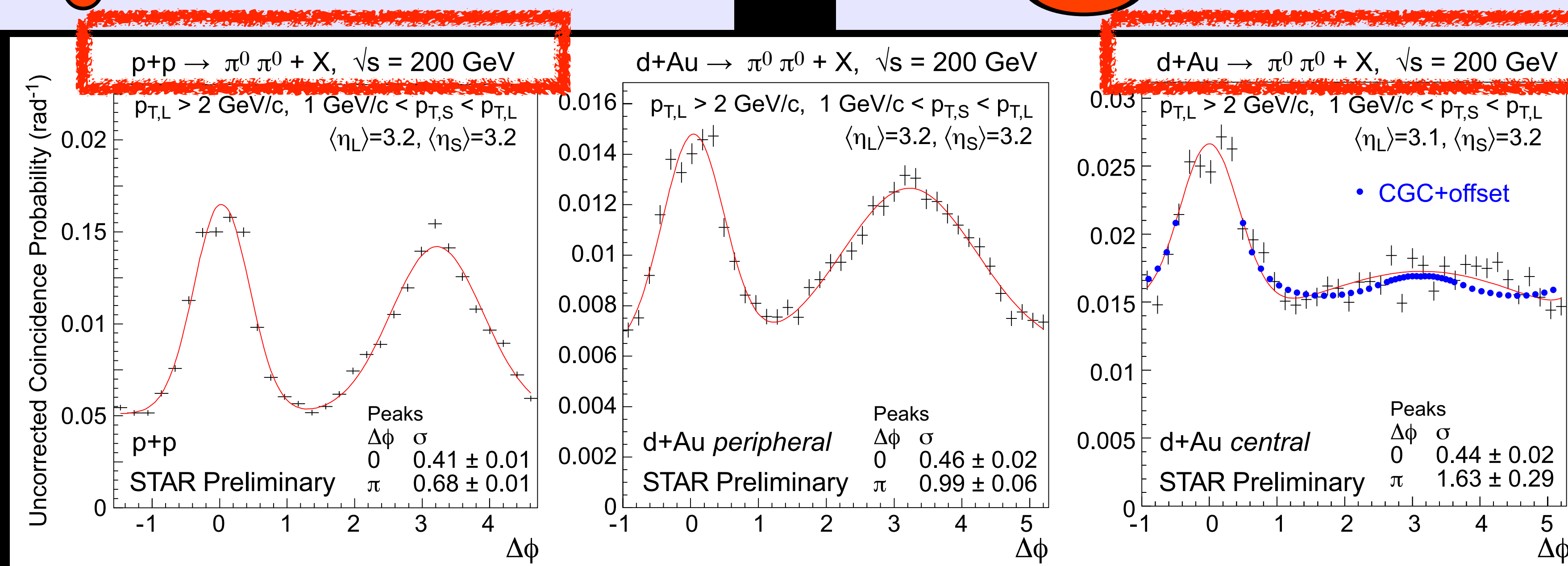

- Saturation inspired model GBW describes HERA ep data
- First such measurements for nuclei for x < 0.01
- wide energy range of EIC is essential for $F_L$

# Key Measurements:

## $k_T$ dependent gluon distribution: Di-hadron correlation

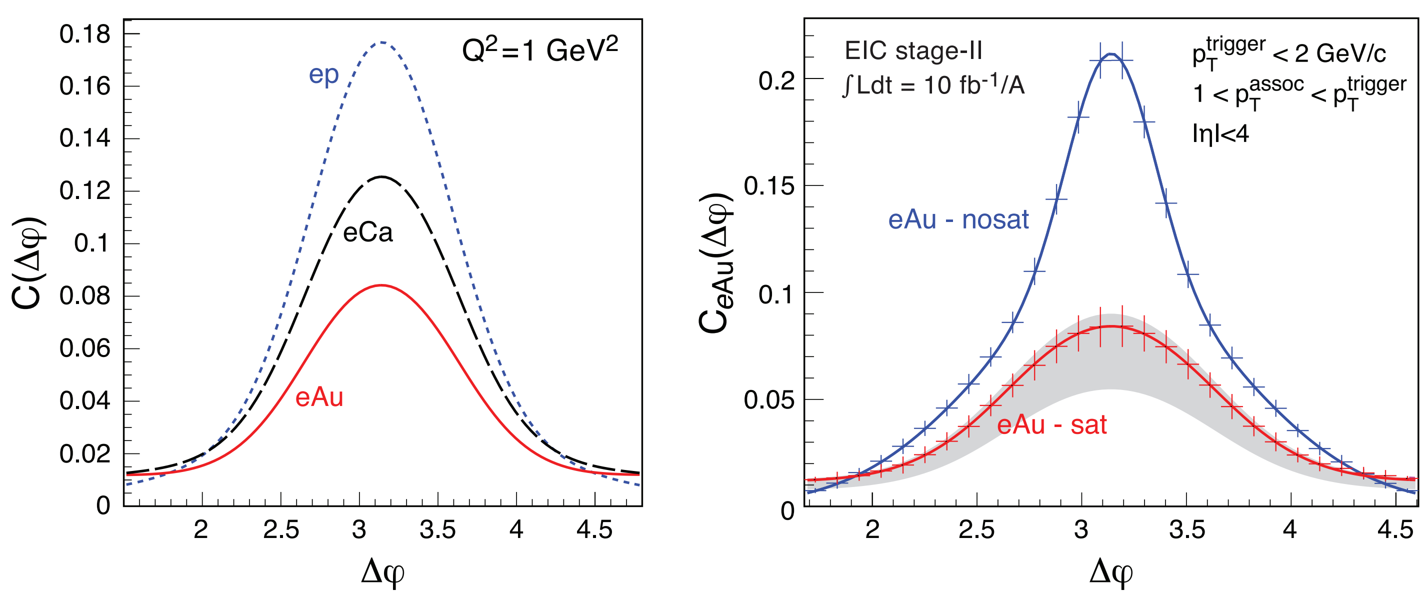


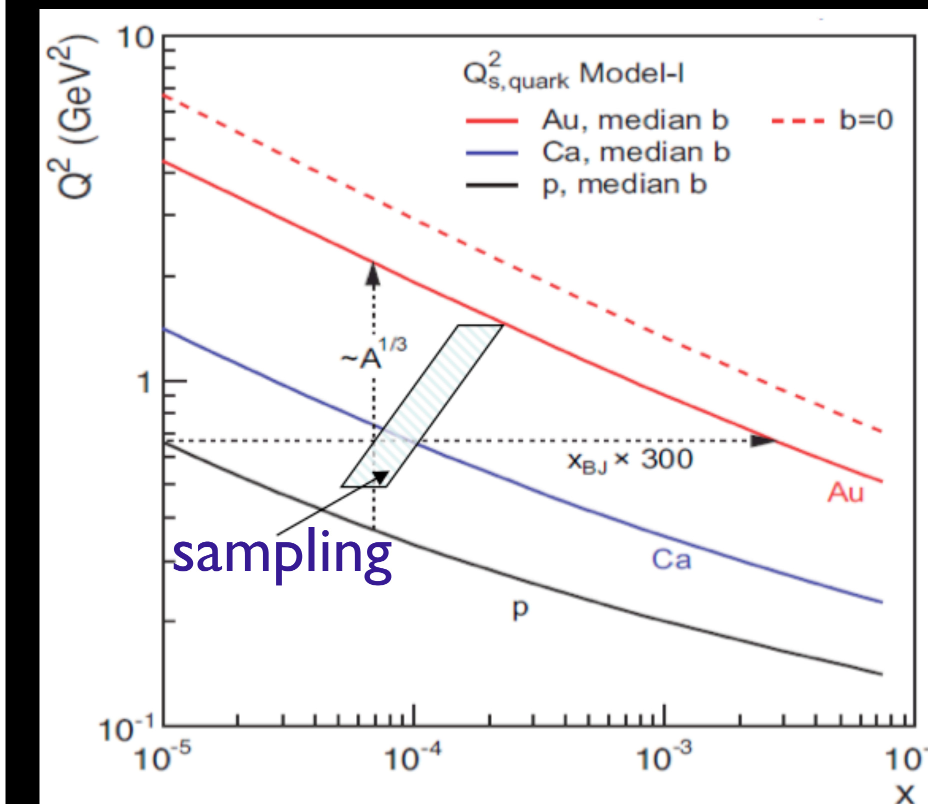




- Multiple scattering in the dense nucleus at forward in dAu lead to mono-jet (decorrelation at ΔΦ=π) in CGC frame work ( J. Albacete and C. Marquet, PRL 105 (2010))
- Estimated $x_A \sim 10^{-3}$

# Di-hadron correlation at EIC

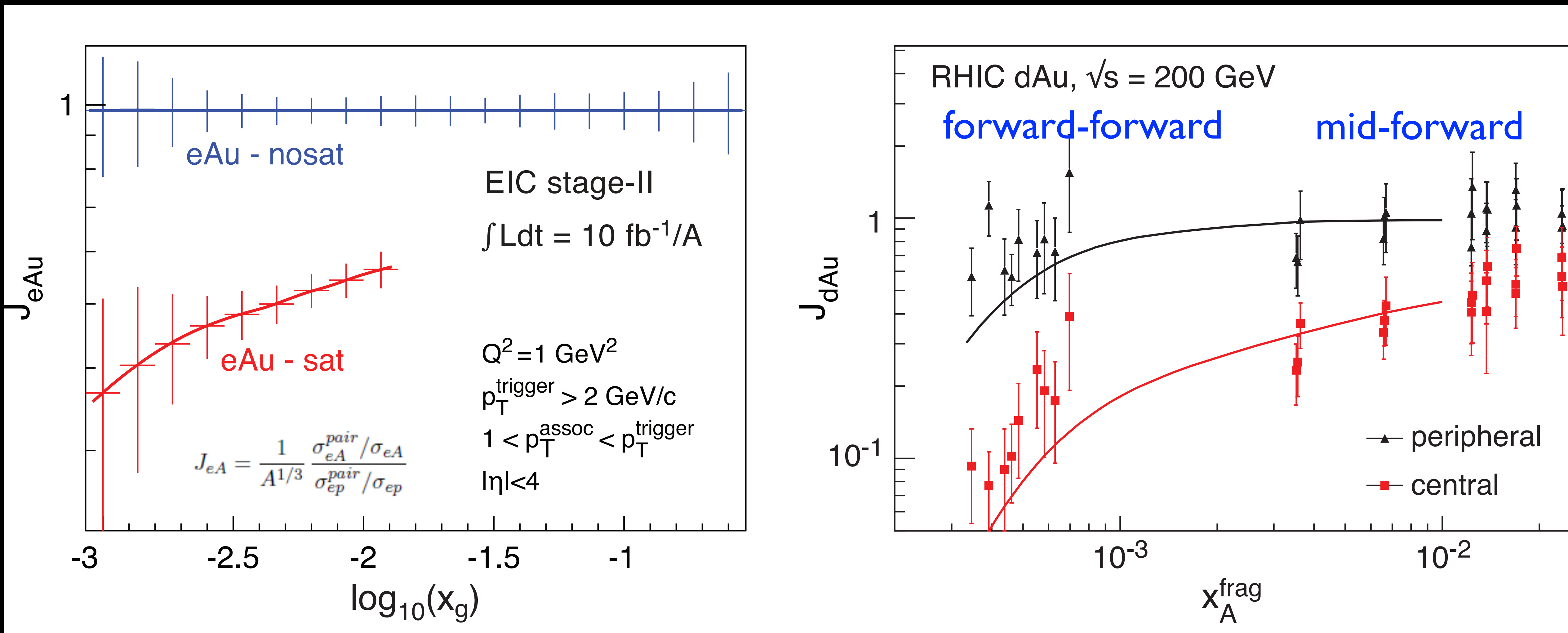



Bowen, Dominguez, Yuan 2011/2012



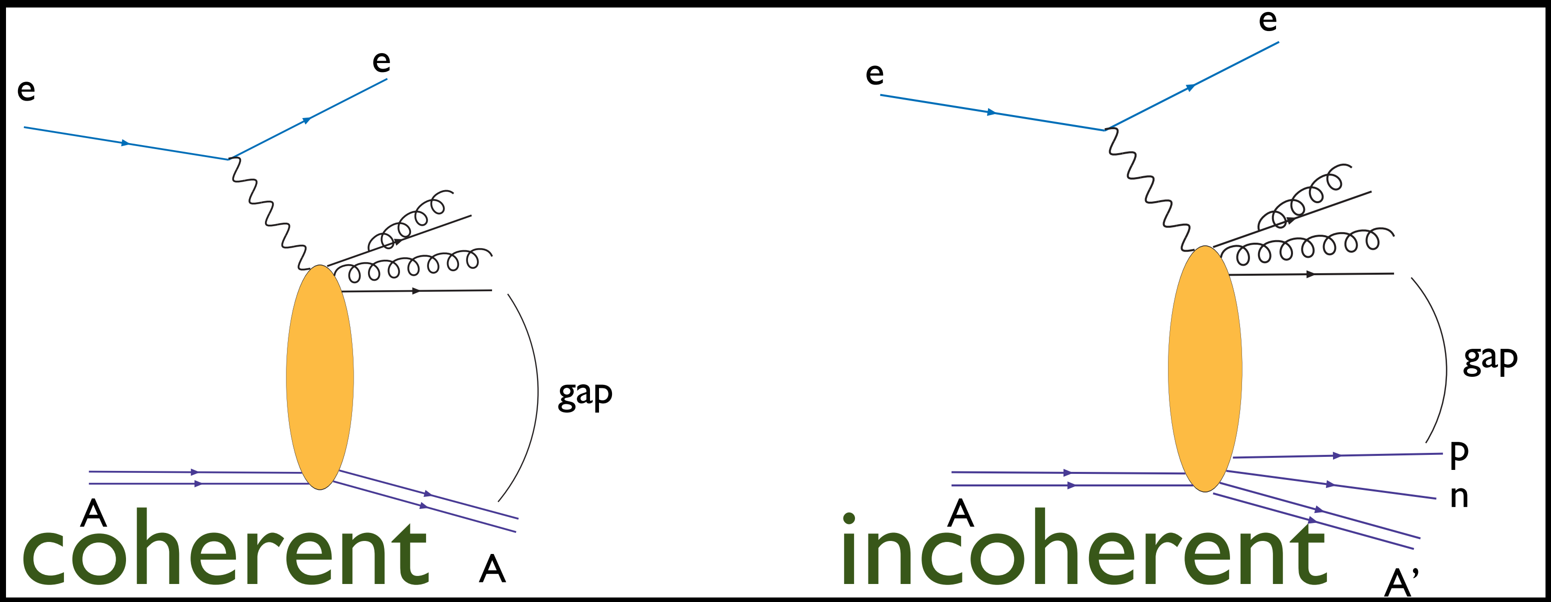

- EIC reach smaller-x regime with clean kinematic control in di-hadron correlation measurement
- EIC expected data from10 fb$^{-1}$ integrated luminosity at 30(e)x100(p/Au) GeV
  - estimated using Hybrid model: Pythia+nPDF+DPMJETIII (without saturation)
  - $Q^2$=1 GeV$^2$   <x>=1x10$^{-4}$
  - hadron $p_T$ cut:  trigger / associate = 2 / 1 GeV/c
  - ~x2 suppression expected in eAu/ep with saturation
- Systematic differential measurement: crossing onset of saturation using √s, $Q^2$, A

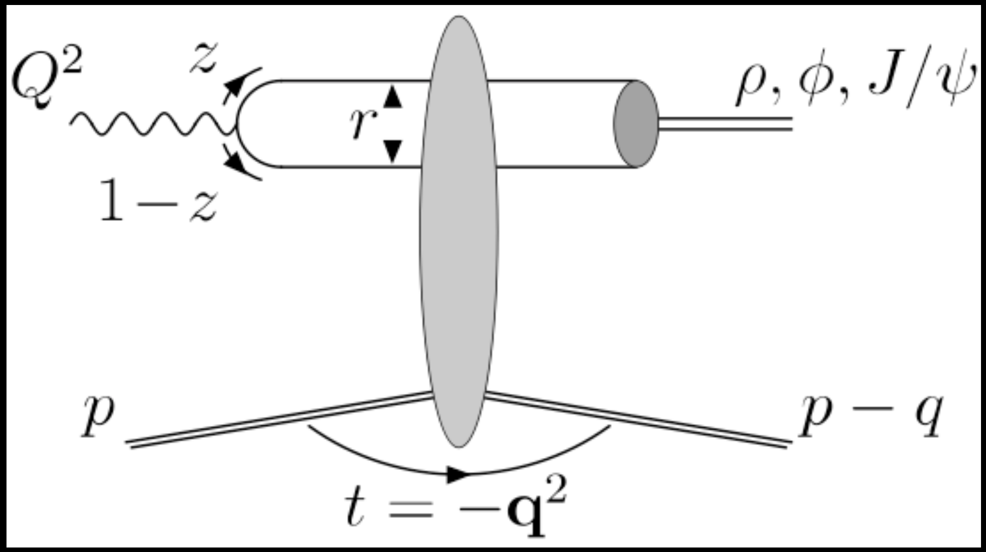
# Di-hadron correlation vs x at EIC: Nuclear modification $J_{eAu}$




- $J_{eAu}$ - relative yield of di-hadrons produced in eAu compared to ep collisions
- Curves from saturation model (B. Xiao (2012) )

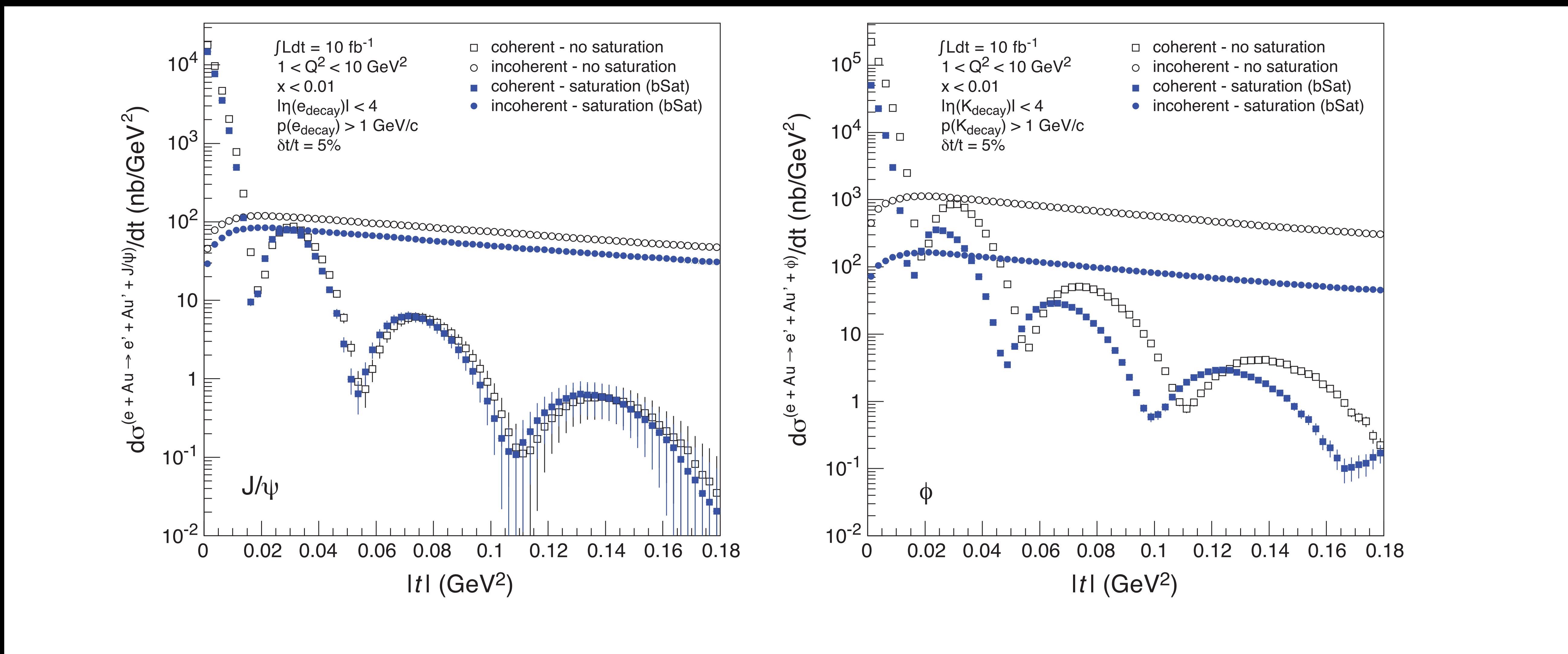
# Key measurements:
# Gluon spatial distribution and correlations in exclusive diffractive Vector Meson production



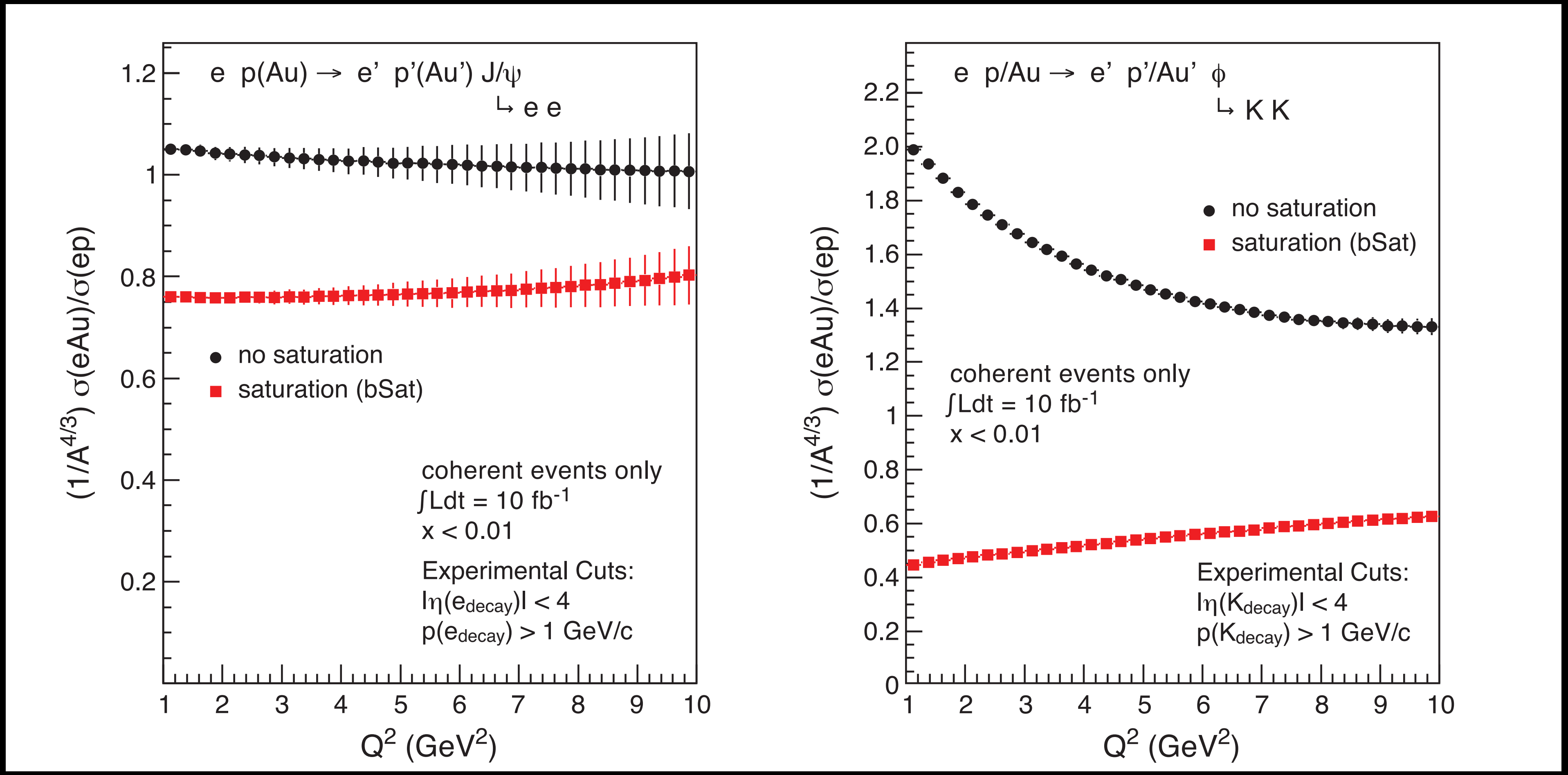

- Novel "strong" probe to investigate gluonic structure of nuclei: color dipole coherent and incoherent diffractive interaction: Sensitive to saturation (s,b,A)
- Large $\sigma_{diff}/\sigma_{total}$ in e+A at EIC (~25-40%)
- Coherent: Access to spatial distribution of gluons
  - Precise transverse imaging of the gluons
  - Modification due to small-x evolution
  - Tagging with Zero Degree Calorimeter
- Incoherent: Gluon correlations in the transverse plane

# Exclusive diffractive vector meson production: J/Ψ and Φ



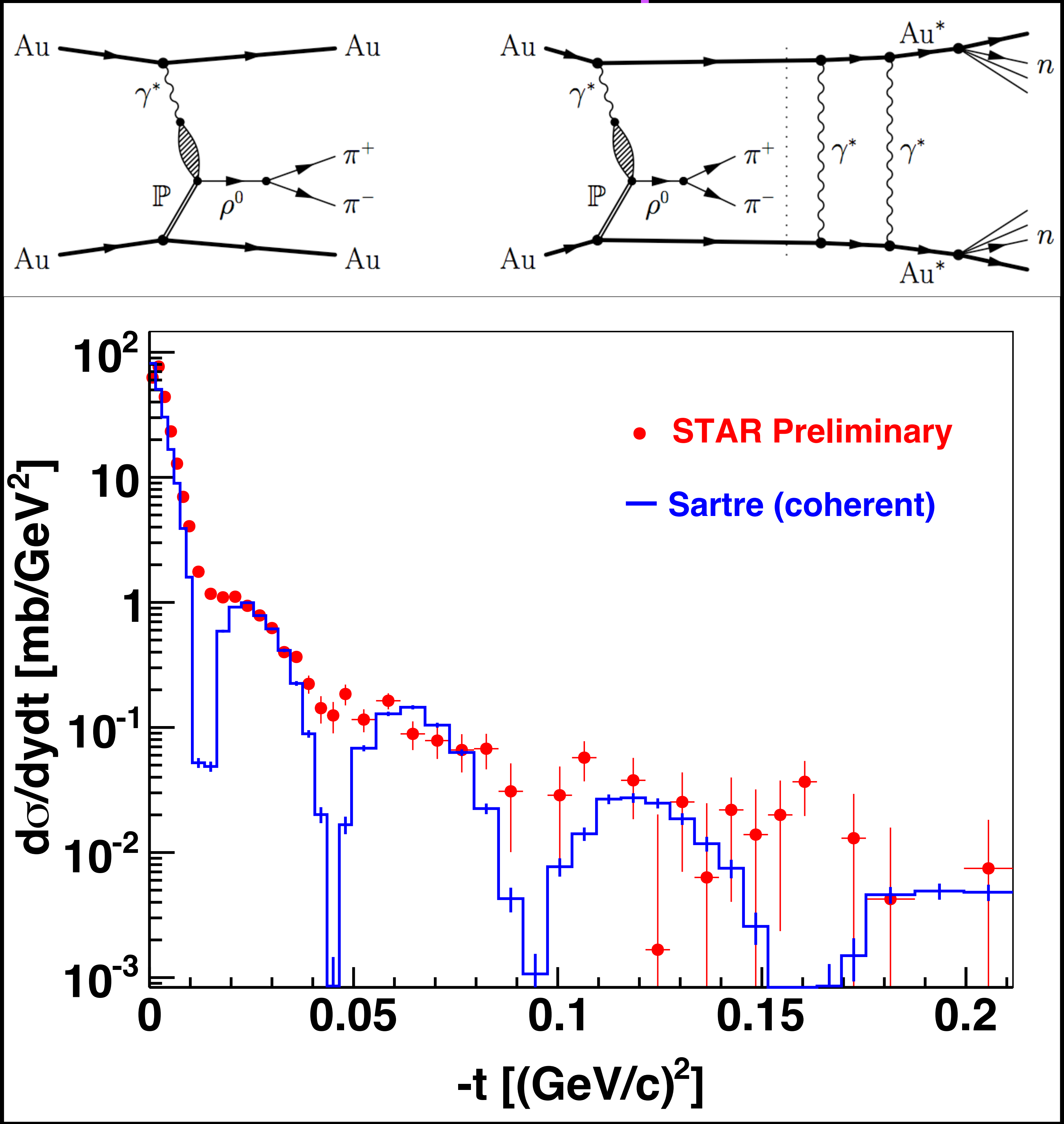

- probe (VM dipole size) dependent exclusive t-dependent production: yield and pattern to saturation
- with A∫Ldt = 10 $fb^{-1}$ with experimental smearing
- Simulation: Sartre (Tobias, Ullrich)

# Exclusive Vector Meson in e+A



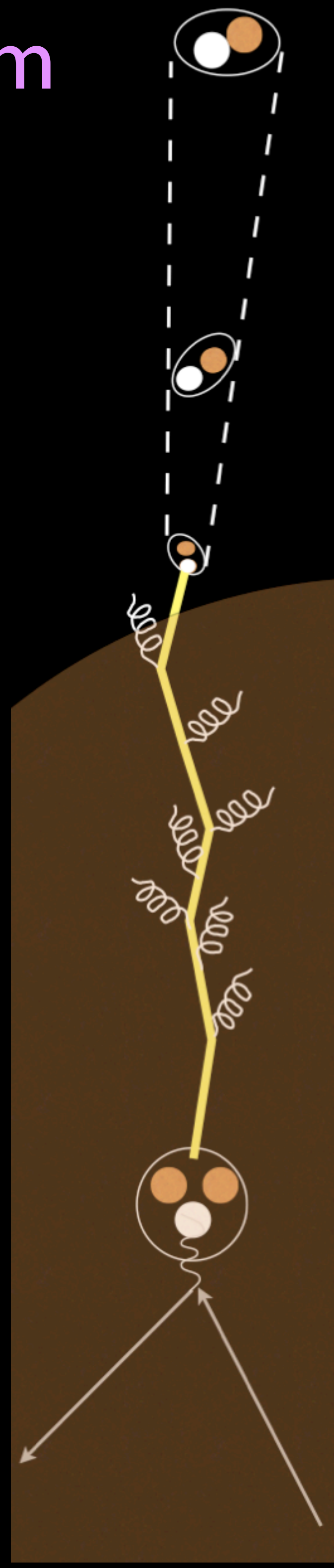

- $Q^2$ dependence of cross-section from coherent VM diffraction
  - $\sigma(eA)/\sigma(ep)$ saturation vs non-saturation
  - With $A\int L dt = 10\ \text{fb}^{-1}$
  - Φ more sensitive to saturation effects than J/ψ due to a larger wave function

# Coherent Diffraction (γ*+IP ) in Ultra Peripheral Collisions at RHIC




- Coherent diffractive ρ production in Au+Au at $\sqrt{s_{NN}}$=200 GeV
- Data: STAR/RHIC Ultra-peripheral AuAu Collision
- Simulation: Sartre

# Key measurements:
# Parton propagation and fragmentation in nuclear medium



- Nuclei as space-time analyzer
- EIC can measure
  - fragmentation time scale to understand dynamics
  - in medium energy loss to characterize medium
    - gluon bremsstrahlung: hadronization outside media
    - pre-hadron absorption: color neutralization inside the medium
- Observable
  - $p_T$ distribution broadening: link to saturation
  - attenuation of hadrons (multiplicity ratio) : energy loss mechanism

# Summary

The new proposed versatile and high-luminosity electron-Ion collider (EIC) is to study one of the outstanding fundamental questions in QCD:

- Establish and explore new degree of freedom of gluonic property of matter - saturation regime by systematically studying the unprecedentedly accessed kinematic regime: gluon saturation at small-x to $Q^2$ evolution at large-x
- Study dynamics and fundamental properties of cold matter: through in-medium fragmentation and parton propagation
- Characterizing the initial gluon dynamics in eA is crucial to disentangle initial and final state effects in RHIC and LHC heavy-ion results